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SECOND QUARTERLY REPORT

RESEARCH IN THE DEVELOPMENT EFFORT OF AN IMPROVED MULTIPLIER PHOTOTUBE

Contract No. NASw 1038

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EXPERIMENTAL TUBE CONSTRUCTION

A number of experimental tubes have been constructed in accordance with the discussion under "Future Plans" in the first quarterly report on this contract. Tube numbers FW-129 - 116444 and 116456 had antimony evaporated on the emitting surface of all dynodes while 116446 and 016530 had antimony on only dynode one. All four of the tubes exhibited very low gain and excessive multiplier noise, so much so as to make testing impossible. FW-129 - 016530 also had an antimony evaporation on dynodes one but showed somewhat better gain and noise characteristics. The techniques, described in the first report, of operating dynode one negative with respect to the defining aperture did not seem to produce the improvements in counting efficiency and lowered dark counting rates expected.

Another tube, FW-129 - 016517, had a single fringe (thickness, .085 micron)[1] MgO evaporated on dynode one. When the tube was first tested just after tip-off, its operation was quite erratic and its output pulses were characterized by the ragged appearance shown in Figure 1. This appearance is not attributed to the pulse amplifier circuits. A standard tube operated in the same equipment shows the normal smoothly decaying pulses. However, this tube now appears to have changed, perhaps due to stabilization of the MgO surface while on the shelf, and now appears to be testable. It is possible with properly prepared MgO surfaces, to enhance the SE characteristics by inducing high voltage gradients through the layer thereby providing an accelerating field to help secondaries generated in the volume of the layer to escape. This effect has yet to be investigated.

Two other tubes having larger defining apertures and magnification smaller than the usual nominal value of 0.7 were built. These tubes, FW-129 - 016514 and FW-130 - 016513, were built with the hope that they would allow the investigation of localized SE characteristics on dynode one. They remain to be tested.

Still another type of tube was built with the variation shown in Figures 2a and 2b. The first two of these types FW-129 - 126443 (Figure 2a) and FW-129 - 126464 (Figure 2b) were hopelessly noisy. The second two, FW-129 - 016539 (Figure 2a) and FW-129 - 016537 (Figure 2b) are quite acceptable tubes, due to special processing. The purpose of these two designs is to attempt to control low energy electron penetration of the defining aperture (A1). FW-129 - 016539 has been quite carefully tested and much of this report is a description of these test results. FW-129 - 016537 has been examined briefly but needs further tests and perhaps design modification to completely evaluate its performance in comparison to that of 016539.

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1 ITTIL Research Communication No. 23 Control of Layer Thickness of Vacuum Deposition During Evaporation by G. Papp.

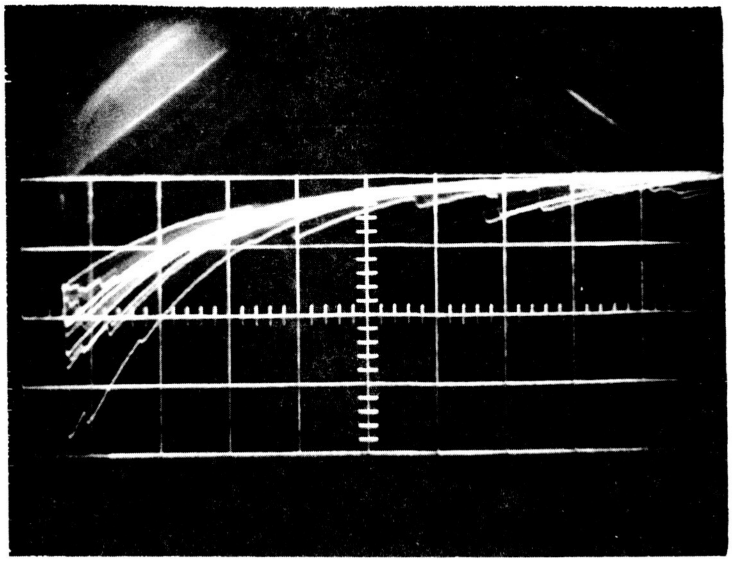


FIGURE 1.

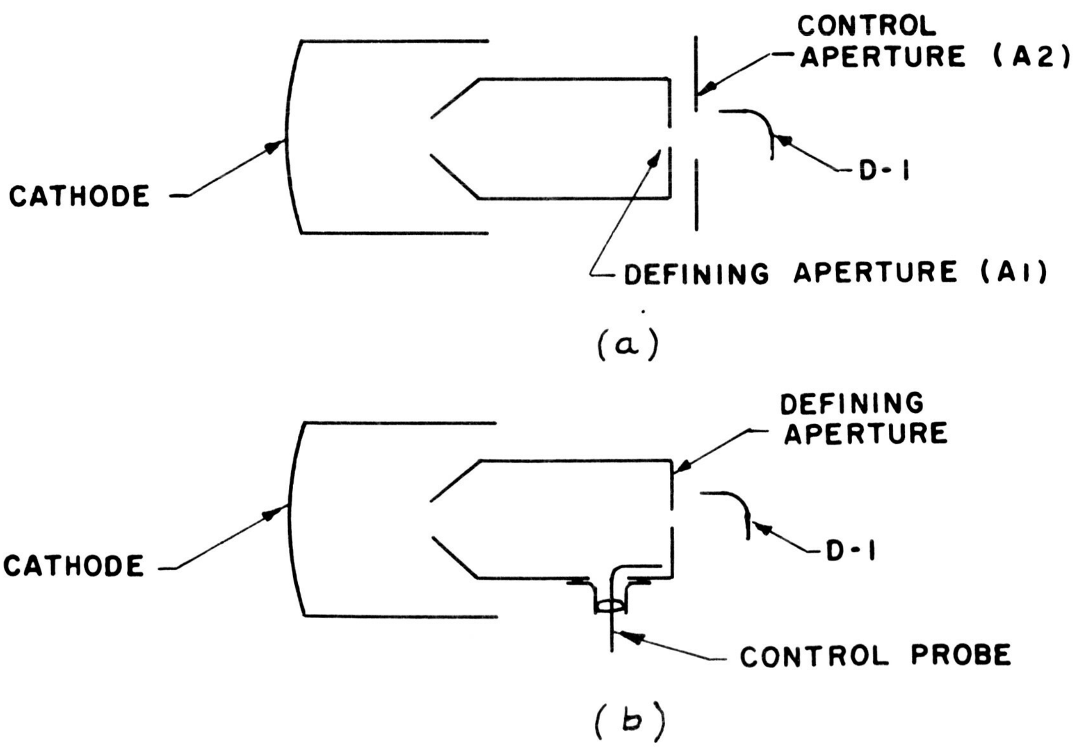


FIGURE 2

CASCADE APERTURE TUBE

As a means of controlling low energy electron penetration of the defining electron aperture while, at the same time, independently controlling the electric field in the region between D1 and defining aperture, a special cascade aperture tube was constructed as shown in Figure 2a. In this tube, (No.-016539) a standard 0.070 inch diameter aperture, A1, was followed by a second slightly larger aperture, A2, (0.100 inch diameter) shielding the bombarded area of D1 from the defining aperture. Figures 3 to 5 describe the resulting interesting behavior of this tube as a function of the various selected operating potentials.

Mode 1: A2 at D1 Potential, A1 Variable

For Figure 3, A2 was operated at D1 potential, interposing minimum field gradients between D1 and aperture, thus simulating the most commonly selected operating condition for standard ITTIL tubes (aperture "tied" to D1). The first aperture, A1, however was operated at various potentials between +40 and -40 volts with respect to A2 and D1, with the measured results for the single electron pulse height spectrum shown in Figure 3. The most striking result obtained was the critical difference in tube behavior between negative and positive operation. With A1 negative with respect to A2 (and D1), the tube was a very poor single electron counter. The pulse height spectrum was nearly exponential, with no well defined most probable pulse amplitude (no peak in curve) and a large increase in smaller-than-expected (< 20 percent $\bar{V}$) pulses even after the dark count was subtracted.

Possibly of equal significance was the large increase in absolute dark counting rates and the "poor" shape of the dark pulse height spectrum.

For A1 positive with respect to A2 and D1, the same tube becomes an excellent single electron counter, one of the best we have monitored to date. The single electron pulse height spectrum has a well defined most probable pulse height with peak-to-valley ratios exceeding 2:1. Thus there is now a minimum of difficulty in assigning significance to near-average-height pulses, (whether or not they should be counted as independent events), and in selecting a suitable bias discriminator level for a counting circuit. In fact, from Figure 3 for positive A1 values, it can be seen that the amplitude of channel 2 or channel 3 near the least probable pulse amplitude would probably represent a satisfactory choice, (counting to all pulses above this amplitude as corresponding to individual input photons). Such a choice is ambiguous for negative A1 values since no tendency toward a least probable pulse amplitude (curve minimum) is then observable.

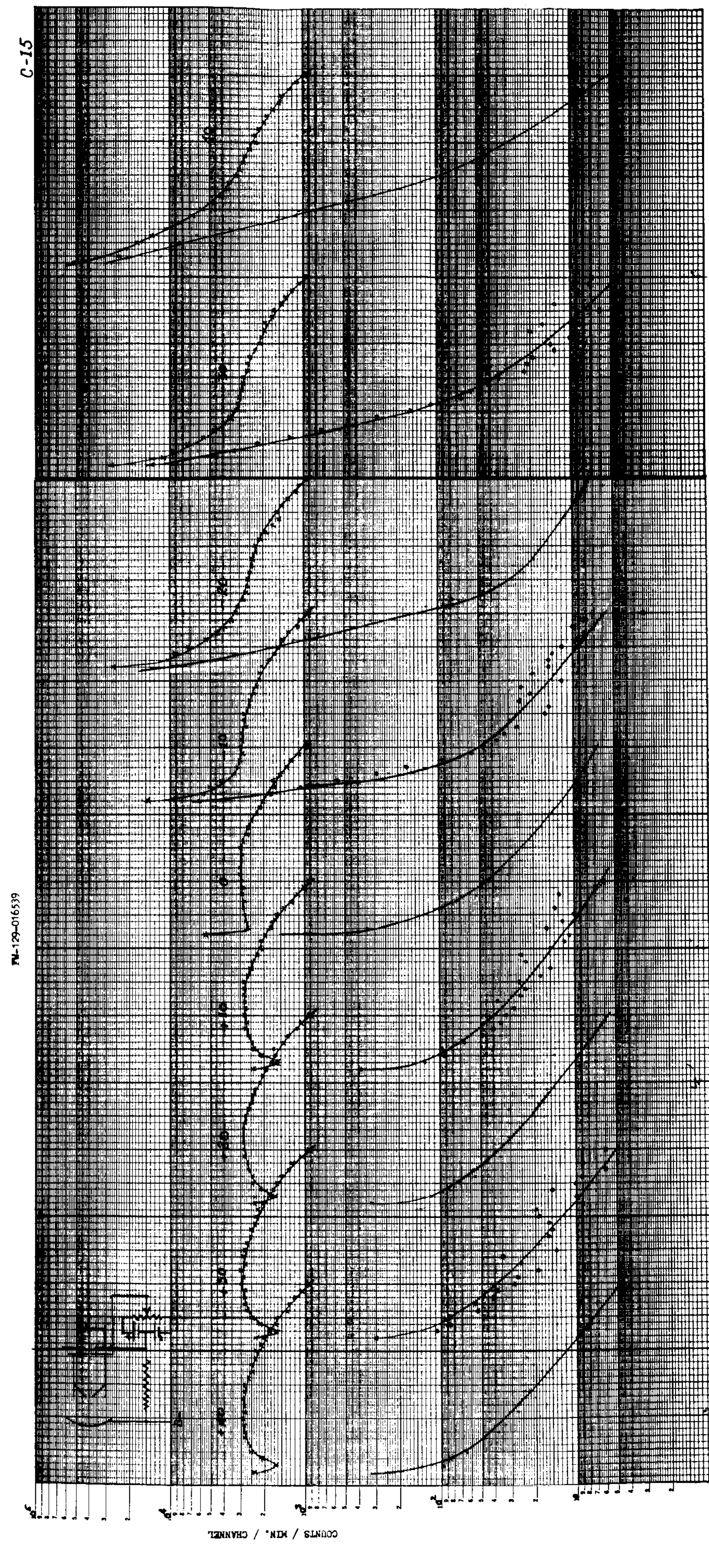
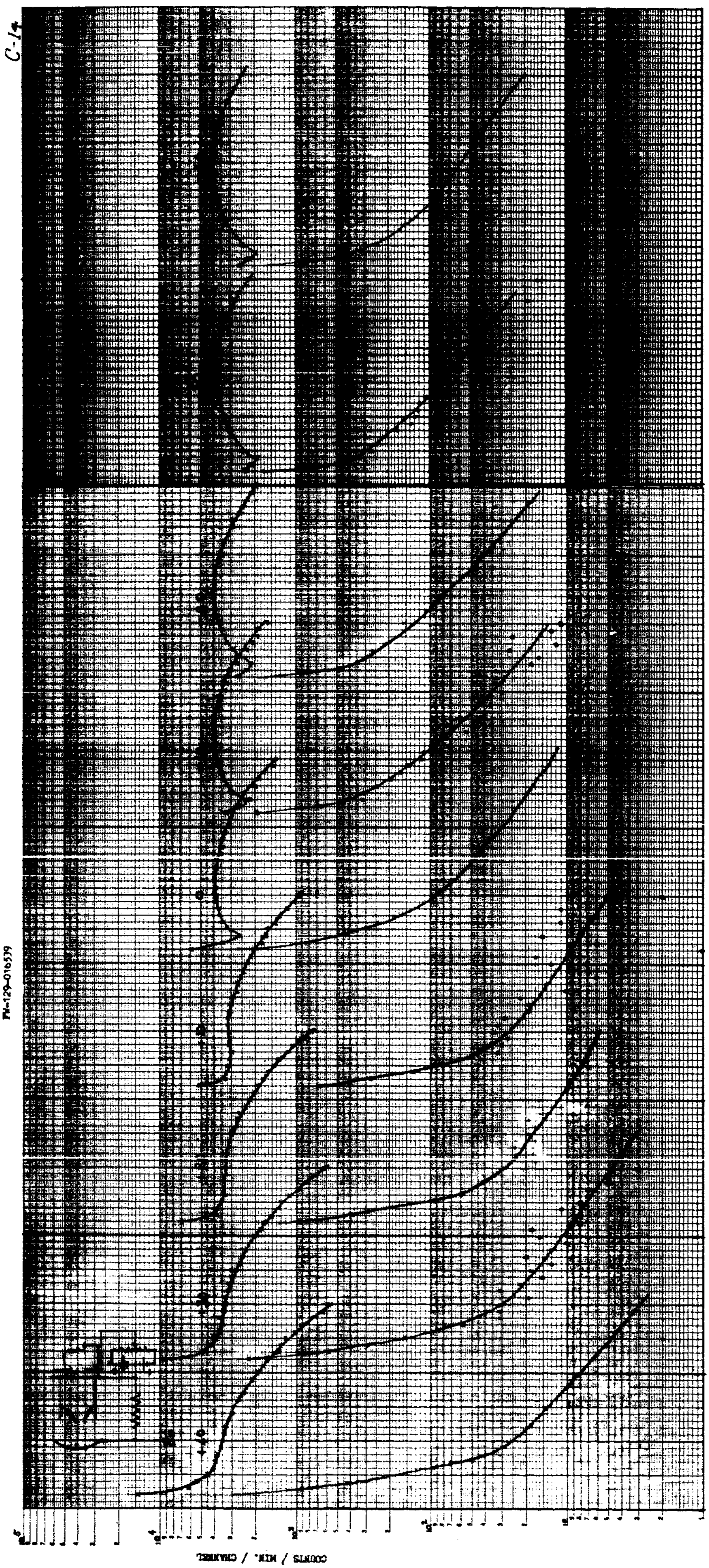


FIGURE 3

PN-129-016539



CHANNEL NO. (1 CH. / DIV.)

FIGURE 4

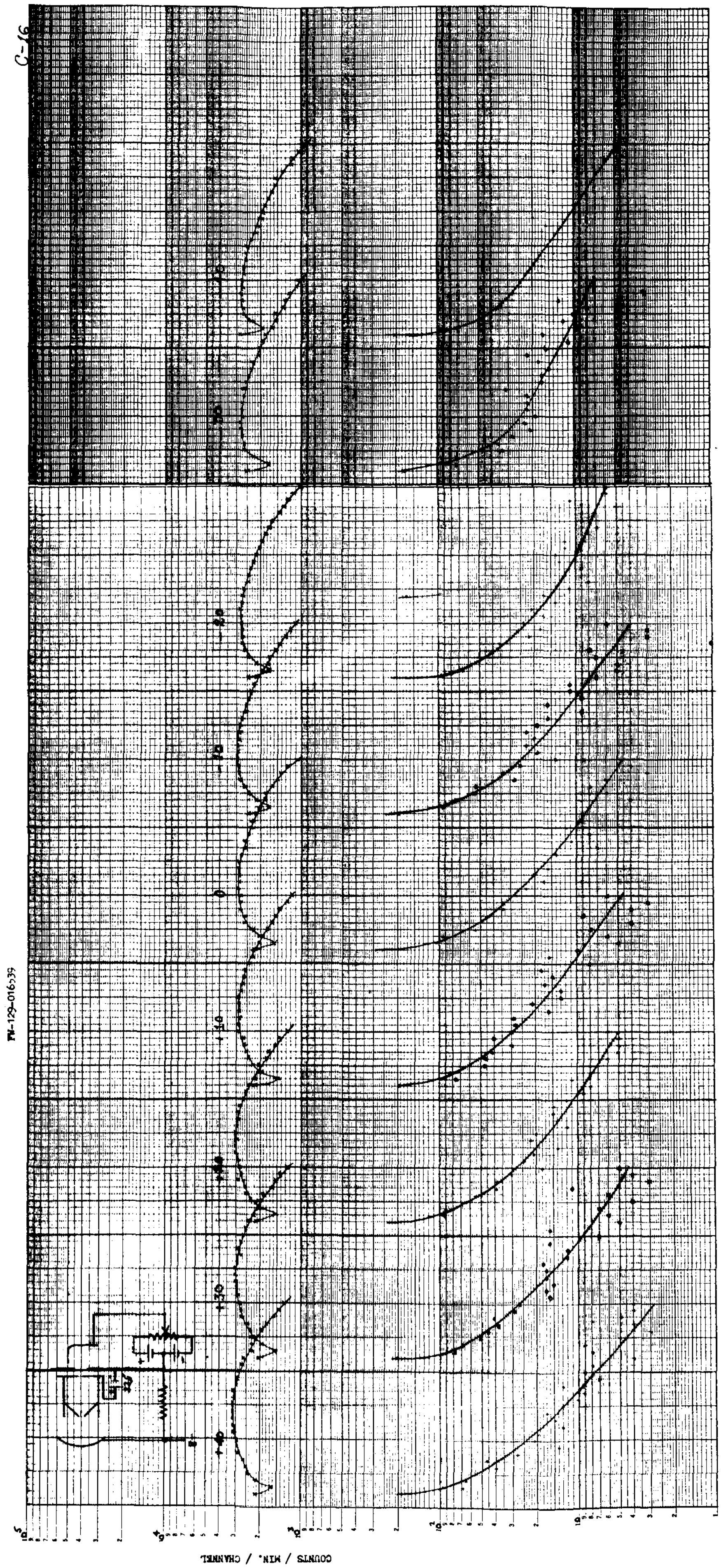


FIGURE 5

Also quite striking from Figure 3 is the marked reduction in dark counting rating with positive A1 values, and the improved shape (with a marked break in the curve indicating a separation of dynode pulse from photocathode thermionic emission pulses). The sharp drop in absolute numbers of dark pulses was not fully anticipated before building this tube, but may be interpreted logically (see below).

Mode 2: A1 at D1 potential, A2 Variable

In an attempt to clarify the electron optical conditions existing in the neighborhood of D1 in this tube, a second set of pulse height spectra was taken with A1 tied to D1 and A2 variable. The results are shown in Figure 4. The poor pulse counting behavior now corresponds to A2 positive while good behavior occurs with A2 negative. The changes are, perhaps, not so evident as with A2 tied to D1, but the trend is the same, even though, in changing A2 as is being done here, the electric field configuration between A2 and D1 is being seriously disturbed. Thus A2 may now be collecting secondaries from D1 when positive and suppressing them when negative, which should markedly alter the pulse amplification properties. The fact that this occurs only to a minimum extent indicates that the major factor is the electric field between A1 and A2 rather than between A2 and D1. Note that the result for the magnitude of the electric field between A1 and A2 is consistent with Figure 3, with optimum counting achieved when the field between A1 and A2 opposes the flow of electrons to D1.

The changes in the dark noise spectrum is not as marked as in Figure 3, a result needing further interpretation.

Mode 3: A1 positive 22-1/2 volts with respect to A2, D1 Variable

Figure 5 shows the test results when A1 is operated at a fixed 22-1/2 volts positive with respect to A2, a reasonable choice for good counting behavior based on Figures 3 and 4, and D1 potential variable. Under these conditions good counting characteristics are achieved throughout the range of ± 40 volts for D1, although some minor variations can be seen. Clearly, the electric field existing between D1 and A2 is not as critical as was indicated by experiments performed on single aperture tube earlier on this contract. It would appear that the collecting field of D2 does reach into the D1 surface adequately, and that the higher energy (about 600 volts) photocathode primary electrons reach the D1 surface satisfactorily regardless of small voltage differentials on A1, A2, and D1.

Mode 4: Same as Mode 2, except cathode masked to small area

In all test conditions in Modes 1 - 3 for this tube, the photocathode was approximately uniformly illuminated within about a 0.5 inch diameter area.

This would simulate tube behavior when looking at a scene of illumination, or with background lighting present while tracking a star, etc. On the other hand, it was established earlier that photoemission from nominally apertured cathode areas did produce anomalous output pulses. Therefore, tube FW-129 - 016539 was now operated with a small (.012 inch diameter) spot of light (optical mask on the photocathode) approximately centered on the effective 0.1 inch IEPD area of the tube. Figure 6 shows the measured test results otherwise under the electrical test conditions of Mode 2. The tube, as before, shows a better pulse height spectrum with A2 negative, but even with A2 positive it shows a peak, unlike Mode 2 operation.

On the other hand, the difference in the dark pulse height spectra remain identical to those of Figure 4, (as they should since only the light on test condition has been changed) with a decided operational advantage for A2 negative.

Interpretation of Cascade Tube Test Results

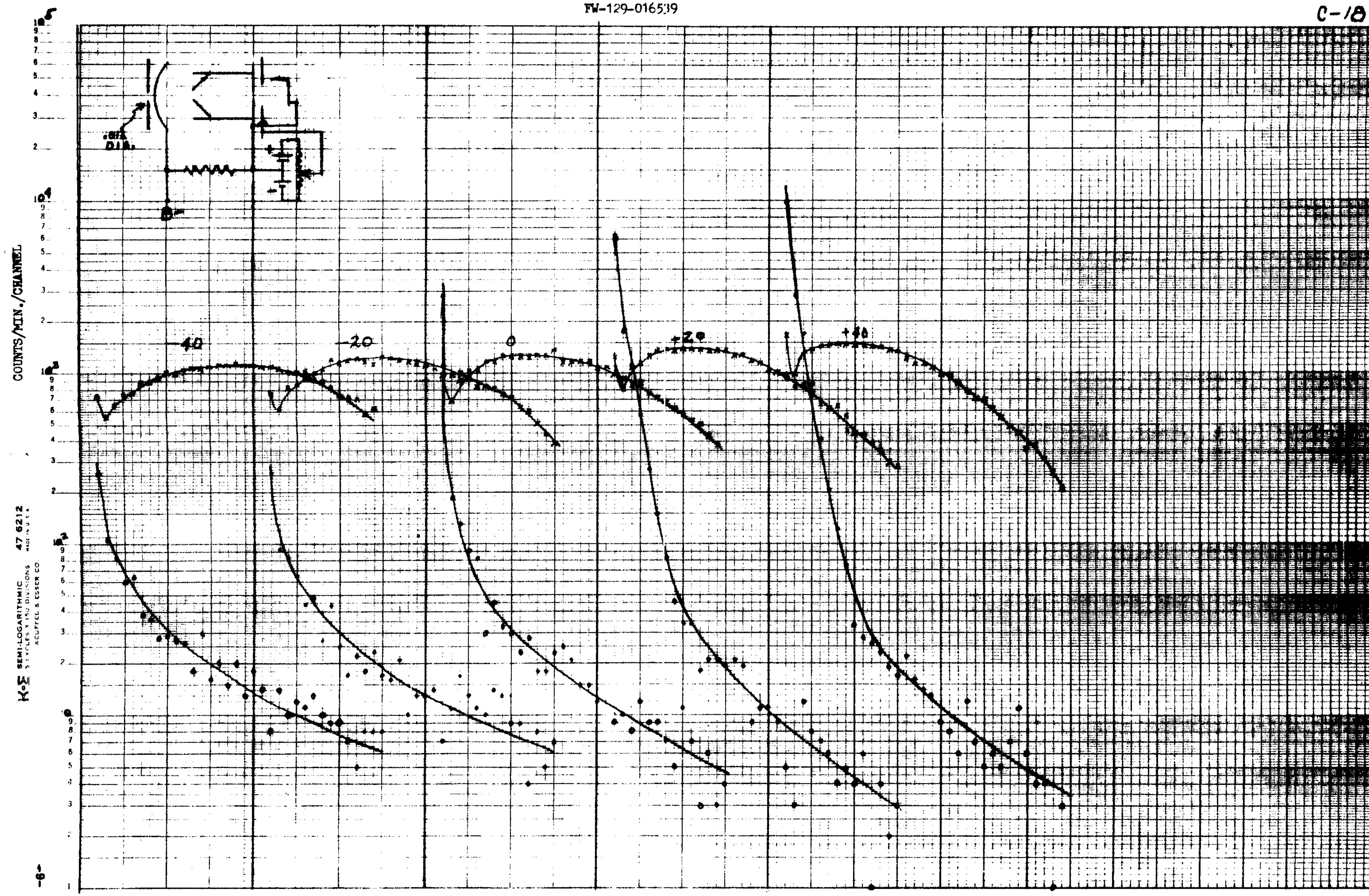
At the risk of premature conclusions, the test results on tube FW-129 - 016539 indicate that a source of low energy electrons exists somewhere between the cathode and the defining aperture of ITTIL tubes. These low energy electrons contribute smaller-than-average output pulses when allowed to bombard D1 (or later dynodes), as would be expected based on their low energy. Their absolute numbers depend on the magnitude of the flooding light on the photocathode outside the nominally active IEPD area, but cannot be entirely removed by optical masking, presumably because of thermionic electrons emitted from the photocathode in these same peripheral areas. They can be prevented (to a large degree) from reaching the multiplier by a comparatively small decelerating field produced between the two apertures, A1 and A2. No sharp minimum required potential is observable for this suppressing voltage, but the minimum test value of 10 volts appears adequate.

The electric field between A2 and D1 is not particularly critical in determining pulse amplification properties, but further analysis of the test results and further experimentation is desirable.

The weak immersion lens action of A1 and A2 at 10 volts differential and 600 volts primary electron energy does not seem to be likely to play a role, especially when the insensitivity to A2 - D1 potential is considered, but may play a limited role in determining the bombarded area on D1.

Several possible sources of the disturbing low energy electrons can be postulated. Possibly the most obvious of these would be secondary electrons produced by primary photocathode electrons (both photo and thermal) striking the defining aperture or internal "anode" surfaces. These secondaries "see" an essentially field free region within the anode cylinder and may find their way out through the defining

FW-129-016539



CHANNEL NO. (1 CH./ DIV.) FIGURE 6

aperture to the multiplier. However, their directional properties with respect to the aperture plate (their prime originating source area) is such that they seem unlikely to do this without positive accelerating fields to the aperture, contrary to the evidence of Figures 3 through 5. An alternate, and possible more likely source of low energy electrons, would be photoelectrons produced on the inner surfaces of the anode cylinder by soft X-ray excitation, the soft X-rays in turn being generated by the primary photocathode electrons striking the aperture plate. Since the primary electrons have sufficient energy (600 volts) to excite soft X-rays efficiently, this could be a source of the low energy "tertiary" electrons, and the resultant tertiary electrons would have directional emission properties appropriate to going through the A1 aperture even at zero A1-A2 potential difference.

Regardless of the explanation of the small output pulses for certain operating conditions, it is clear that a means (cascade apertures) has been found to control the output pulse height spectrum and create a more satisfactory pulse counting tube. Although cascade aperturing may not be the most practical way of achieving this performance, it has permitted us an insight into tube behavior which should enable us to develop more suitable pulse counting tubes, the basic objective of this contract. Certainly the possible presence of anomalous low energy electrons and X-ray effects in the "front end" section of multiplier phototubes must be carefully considered in all pulse counting tube designs. For example, in "ordinary" scintillation type multiplier phototubes in which the bombarded surface of D1 is exposed by rather large solid viewing angles to the photocathode, X-rays generated at D1 may return to the photocathode producing added electrons and consequent spurious after-pulsing. This might be a possible explanation of the experimental results of Tusting, Kerns, and Knudsen in which they observed few smaller-than-expected output pulses when the multiplier phototube was gated on for observation only when a light pulse occurred.

COOLING TESTS

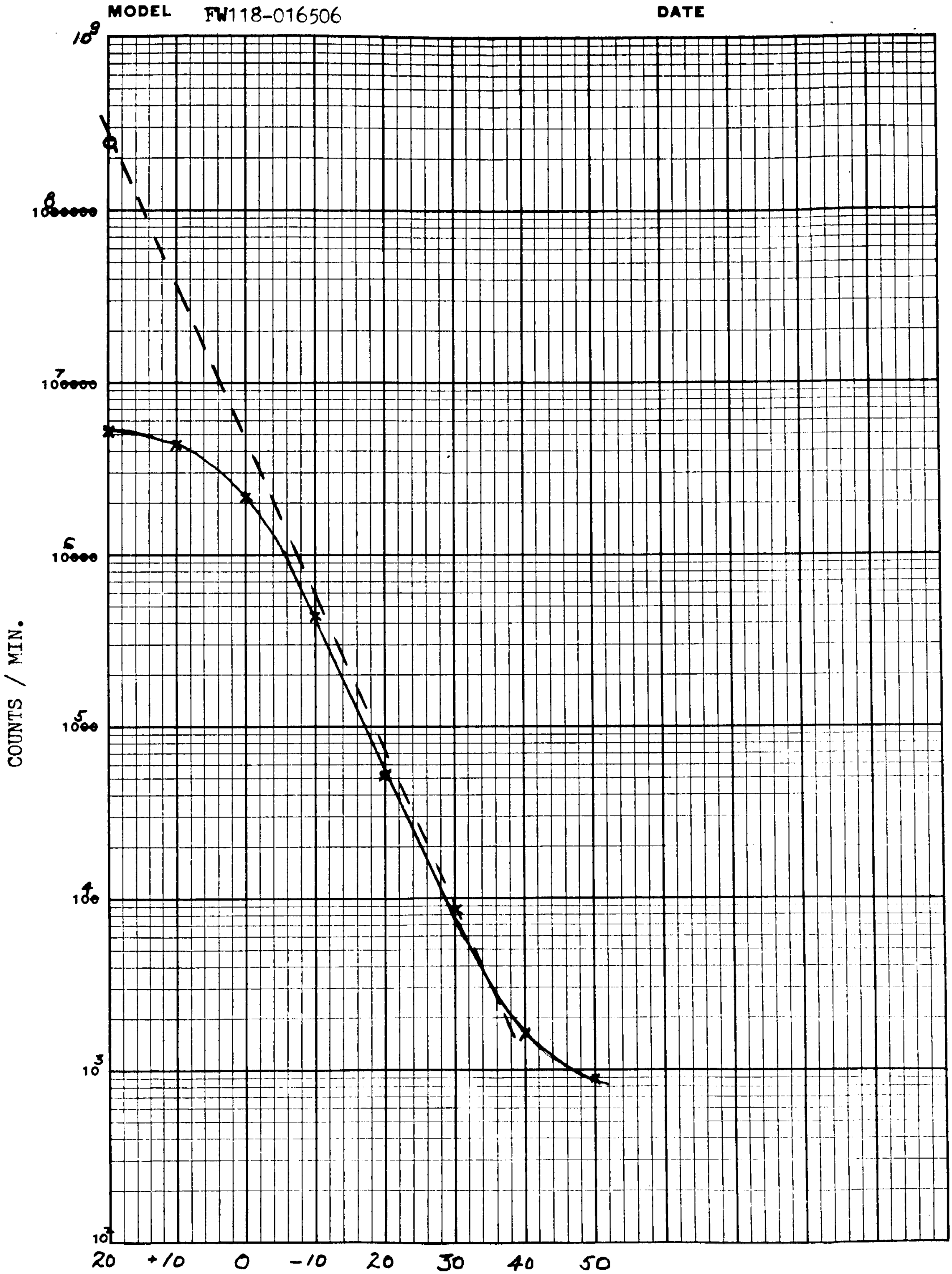
Although it is recognized that NASA has minimal interest in detectors requiring colling for long term operation in space, yet the interpretation of cooling characteristics on multiplier phototubes is nevertheless desirable because of the insight it provides into tube operating principles. Furthermore, tubes with low thermionic dark current at ambient temperature, or even at elevated temperatures are needed for space applications. Also, since moderate cooling by radiometric methods is quite feasible in space, the improvement expected in multiplier phototubes should be established. For this reason, ITTIL has performed a few cooled tests on pulse counting tubes, primarily of the S-1 photocathode variety. Although, such S-1 tubes are high in thermionic dark current, they offer probably the best means of detection between 0.8 and 1.2 microns, a spectral region covering many important radiation sources, including several practical laser wavelengths.

Figure 7 shows a thermionic pulse count curve as a function of cathode temperature for FW-118 - 016506. Note that the curve saturates near room temperature at a maximum counting rate of about 5.5 x 10^6 cpm. Suspecting that this was due to pulse overlap and the finite resolving time of our pulse circuits, we measured the d-c output current at room temperature, using our standard test procedures to measure multiplier gain, and converted to the total number of expected input electrons per minute (counts per minute with 100 percent counting efficiency). The resulting point fell closely upon the non-saturated rising portion of the cooling curve, confirming our prediction of circuit resolving time problems. Note that, with this correction this tube did follow an approximate Richardson law, i.e. falling exponentially with temperature over small temperature changes. ITTIL Applications Note E4 describing these cooled characteristics is attached to this report.

Other tubes do not cool as well as FW-118 - 016506 above. Figure 8 shows a test run on another FW-118 - 036402 in which the counting rate as well as the dc dark current reached a sudden saturation at about -20 to -30 degrees C. This residual current is at least partially originating from the photocathode, since both dark current and dark count fall further if the cathode is biased off by changing it to D2 potential. An explanation of this behavior has not been found, but it may be due to stray light leakage in our rather crude cooling apparatus. Figures 9, 10, and 11 give the test results on three additional experiments made to clarify the role of photocathode thermionic emission on dark noise. In all three cases, standard ITTIL FW-118 tubes, constructed on other funds, were used. The total dark noise spectrum of these tubes was then measured as a function of the faceplate temperature (no intentional multiplier cooling). As can be seen, the portion of curves corresponding to larger pulses, above approximately channel 5 to 10 in amplitude, drops rapidly with cooling, approximately an order of magnitude for each 10 to 15 degrees C.

In Figures 10 and 11, this drop in large pulse numbers becomes ambiguous below about 0 to -10 degrees C, with the effects of further cooling becoming indeterminant, because of the very low pulse rates observed (below 1 to 10/.1 min./channel) and the obscuring effect of smaller dark pulses presumed to be dynode noise pulses. In Figure 9, however, it can be seen that further cooling into the -60 degrees C region produced a further drop in the larger output pulses, as expected. The inconsistency in the curves of Figure 9, with the curve for -5 degrees C showing more pulses than the curve for 0 degree C, is believed to be due to gross undertainties in the calibration of our cooling apparatus, presently a makeshift affair, with only the cathode cooled and a thermocouple not integrally attached to the faceplate of the tube. Nevertheless, the general trend downward with cooling is clear.

The change in slope of the curve for 23 degrees C for increasingly larger pulses is believed to be related to the finite resolving time of the pulse circuits and subsequent overloading as confirmed for tube FW-118 - 016506. If this tentative explanation is correct, a slope measurement of this type may be useful in checking for overload experimentally.



DEGREES CENTIGRADE FIGURE 7

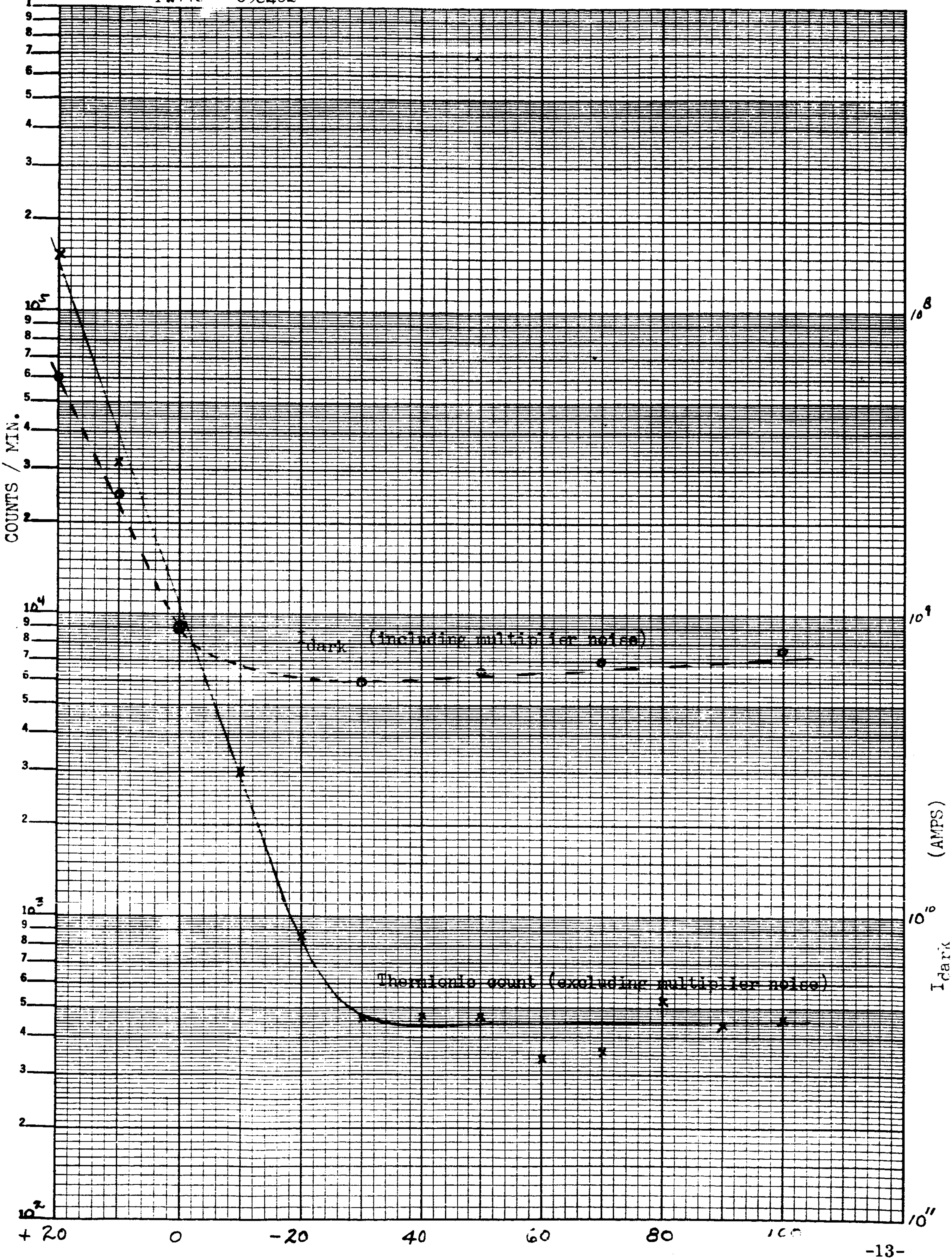
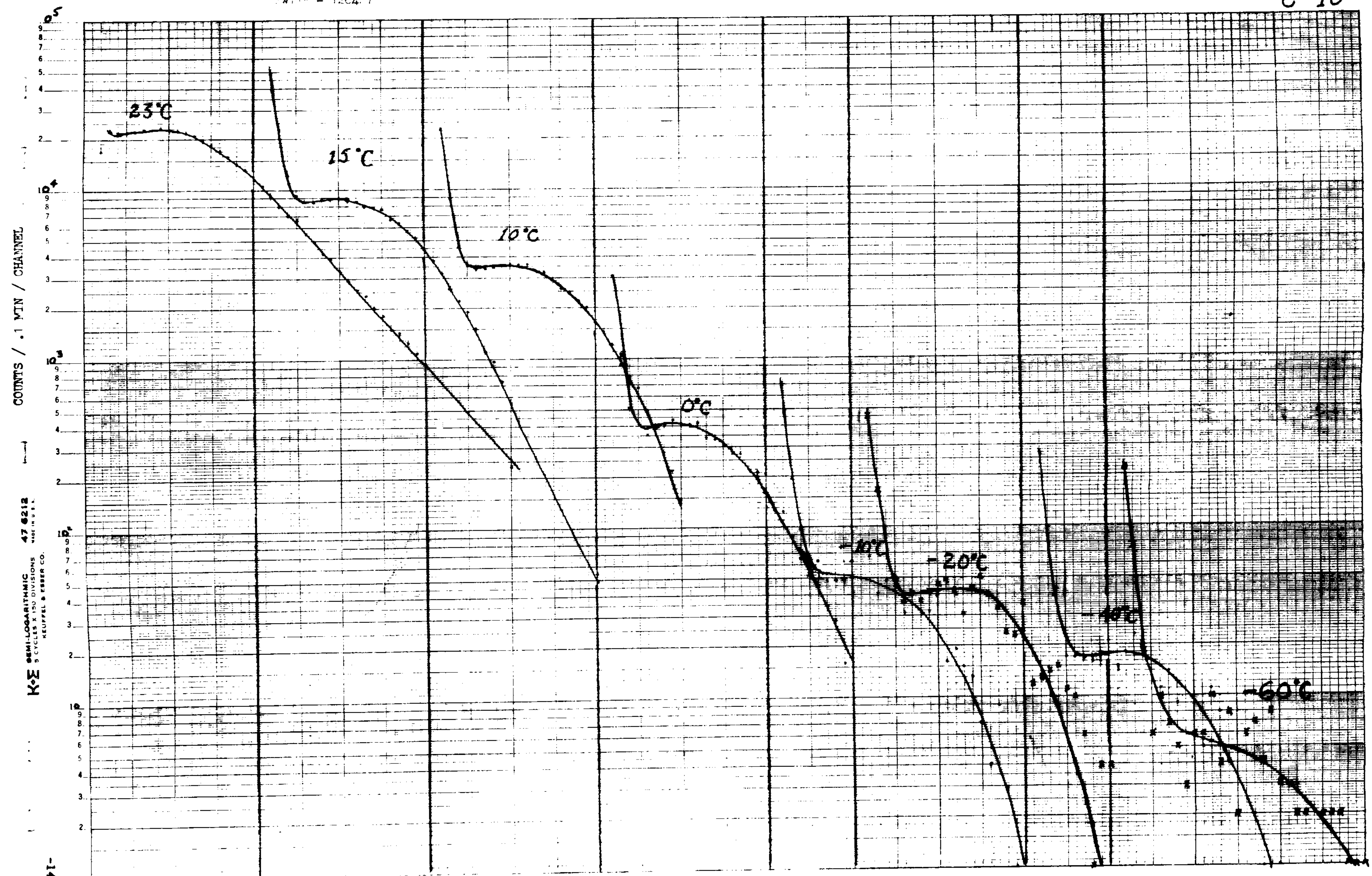

COUNTS / MIN.
I_{dark} (AMPS)
I_{dark} (including multiplier noise)
Thermionic count (excluding multiplier noise)
10^5
10^4
10^3
10^2
10^8
10^9
10^{10}
10^{11}
+ 20
0
-20
40
60
80
100
DEGREES CENTIGRADE

FIGURE 8

80

EW118 - 126427

C-10



CHANNEL NO. (1 CH. / DIV.)

FIGURE 9

FW118 - 1164CE

C-11

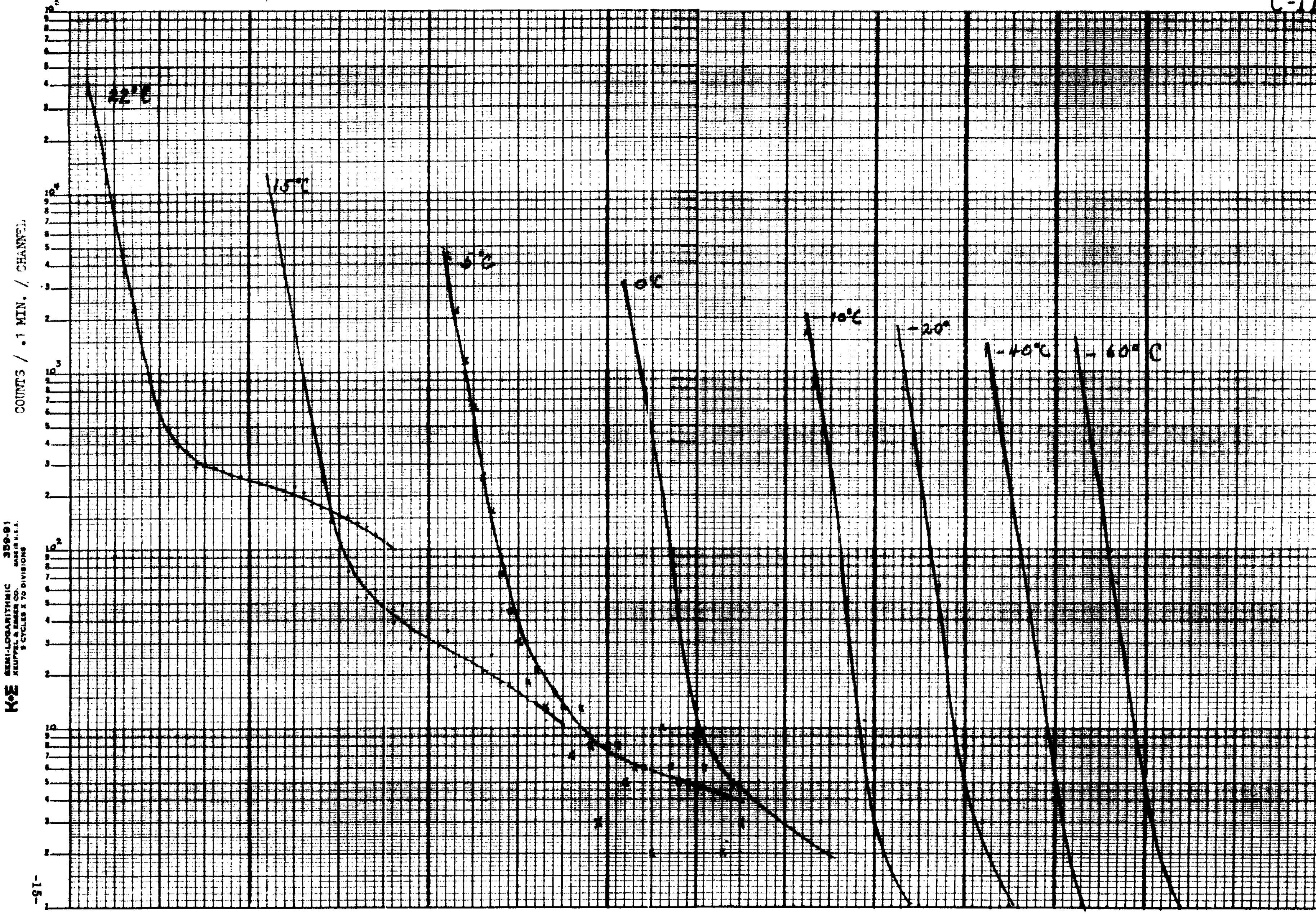


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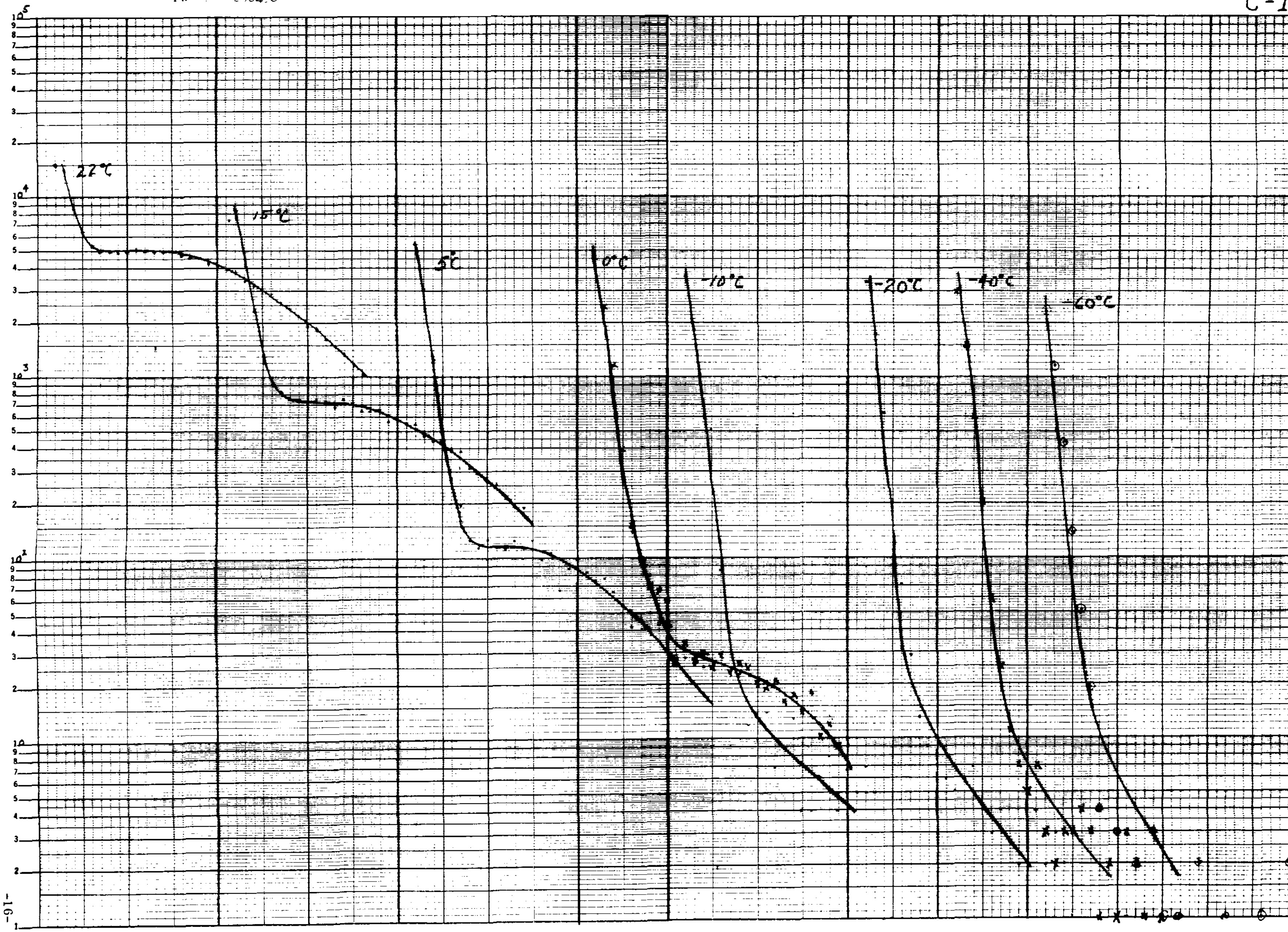
FIGURE 10

FW118 - C96436

C-12



CHANNEL NO. (1CH./DIV.) FIGURE 11

APPENDIX I

APPLICATIONS NOTE E4

APPLICATIONS NOTE E4

COOLING CHARACTERISTICS OF ITTIL MULTIPLIER PHOTOTUBES

The appreciable contribution of thermionic emission from the photocathode to the anode dark current observed in some multiplier phototubes makes possible a reduction in this current and consequently in the dark noise of these tubes by cooling. Figure 1 Curve (a) shows the measured decrease in anode DC dark current, I_{DC}, in an ITTIL FW-118 multiplier phototube (S-1 type) down to photocathode temperatures of about -20 degrees C. The sharply falling dark current, approximately following a Richardson type law, substantiates the predominance of thermionic emission from the photocathode in this tube at these temperatures. A decrease of about an order of magnitude for each 10 degrees C of cooling is observed.

Figure 1 Curve (b) shows the corresponding decrease in the equivalent noise input (ENI)[1] as a function of temperature, compared to the published[2] ENI characteristic Curve (c) for a competitive type tube. The FW-118 starts with a lower ENI characteristic at room temperature (at least partially because of its smaller effective photocathode area) and improves about twice as fast as the competitive detector with temperature.

At anode dark current levels below about 10^{-10} amperes, reliable and significant cooling characteristics can only be observed with difficulty in many multiplier phototubes because of the erratic and nonreproducible contribution of leakage currents (in the tube stem and base and internal parts), external pickup effects, and other low current measurement difficulties. For example, a resistance of 10^{13} ohms across the surface of nominally insulating internal anode pin support (an entirely reasonable value in view of the chemically reactive cathode materials present) can contribute 10^{-10} amperes in the typical operating range of 10^3 volts. This difficulty may be further aggravated when cooling a complete tube envelope if condensation of water vapor across various tube stem and basing lead connections occurs. Noise from this latter source can be particularly troublesome if the condensation occurs between the tube stem and base, where moisture may be trapped in the base cementing process. To avoid this, ITTIL recommends the use of unbased tubes (flying lead construction) or photocathode-only cooling.

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1 Defined and measured according to IRE publication No. 62IRE7.S1.
2 RCA tube manual, 7102 tube type.

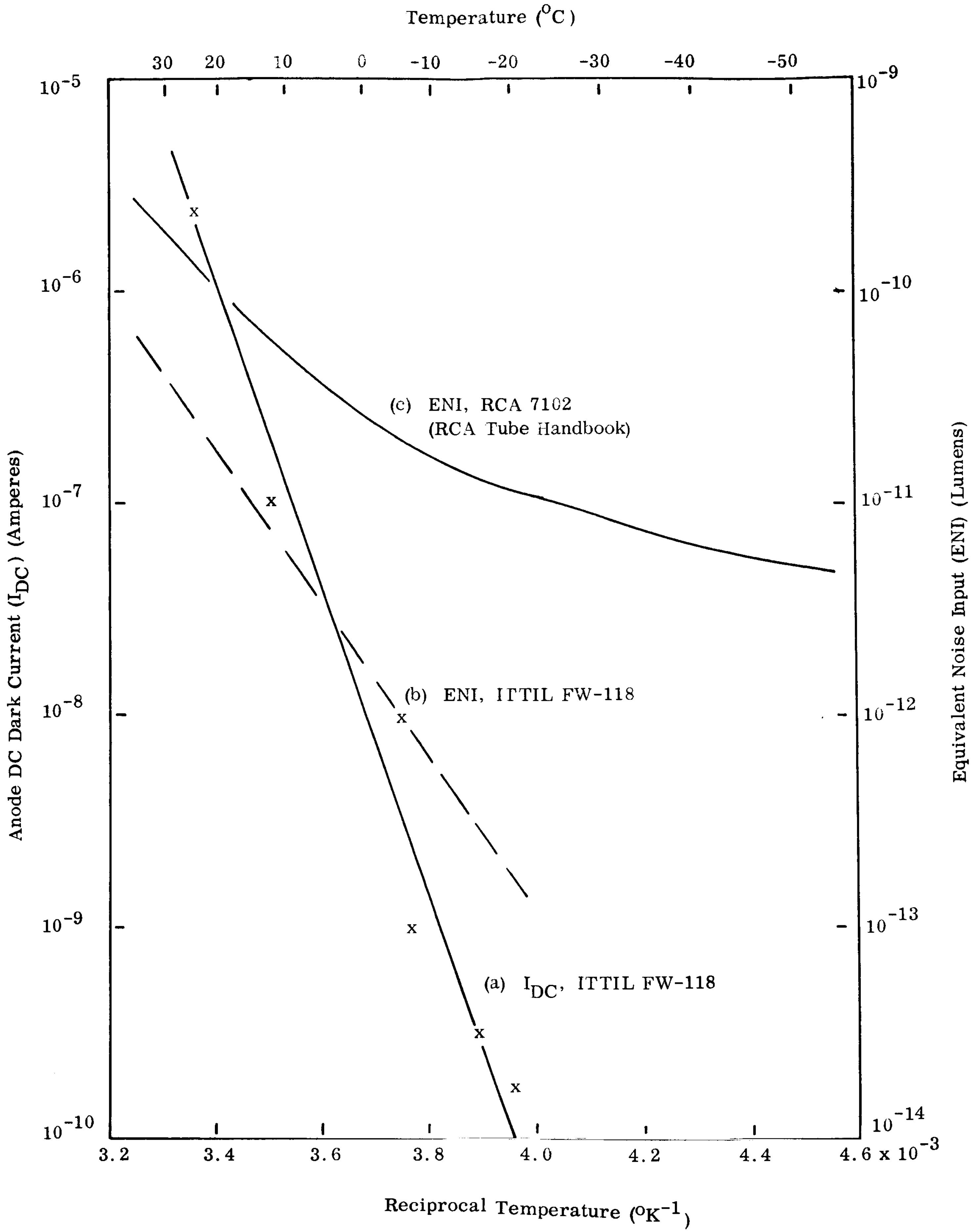

Figure 1 Anode DC Dark Current and ENI Vs Temperature for S-1 Type Multiplier Phototubes

Figure 2 shows a sketch of one type of laboratory cooling test equipment used by ITTIL. The cooled dry gas cools the tube faceplate and thus the photocathode by direct thermal contact, while the warm dry gas keeps the outer window from frosting. For field purposes, thermoelectric photocathode coolers of moderate cooling capability may be entirely adequate.

A recent and unique step taken by ITTIL to minimize internal tube leakage current and therefore improve both the room temperature and cooled dark current-dark noise characteristics, is the addition of an internal guard ring electrode surrounding the anode pin. This guard ring, when operated at quiescent DC anode potential as shown in Figure 3, bypasses surface leakage current around the anode pin and reduces the resultant minimum DC current levels to the order of 10^{-12} amperes or less. If so desired this guard ring can be voltage-driven in the more sophisticated types of feedback electrometer circuits.

For ultra-low light level detection problems, ITTIL normally recommends the use of single electron counting techniques[3,4]. By individually counting the comparatively large pulses produced in the anode circuit of multiplier phototubes resulting from single photoelectrons from the photocathode and biasing off the smaller pulses resulting from leakage current, dynode emission, etc., maximum differentiation between signal and dark noise can be achieved.

Further cooling of ITTIL tubes below the levels shown in Figure 1 is entirely feasible, the tubes being capable of operation at dry ice temperatures and probably as low as liquid N_2 temperatures. A. T. Young of Harvard Observatory has reported[5] a slight increase in over-all sensitivity for these tubes at dry ice and liquid N_2 temperatures combined with a reduction in dark current of at least 5 orders of magnitude at dry ice temperatures, indicating reasonably satisfactory performance, while W. A. Baum has reported[6] dark counting rates below 10 per minute at similar temperatures. ITTIL does not recommend cooling below dry ice temperature unless the temperature cycle is slow enough (a matter of hours) and applied uniformly to the complete tube to prevent strains from developing in the tube envelope, and unless the resultant ultra-low dark thermionic emission rates are known to be desirable (in many

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3 E. H. Eberhardt, "Multiplier Phototubes for Single Electron Counting", IEEE Tr. of Nucl. Sc., Vol. NS11, No. 2, 48, 1964.

4 ITTIL Research Memos 367 and 387, and Applications Note E5.

5 A. T. Young, Applied Optics, Vol. 2, 51 (1963).

6 W. A. Baum, Vol. II, Astronomical Techniques, U. of Chicago Press, 1962, page 28.

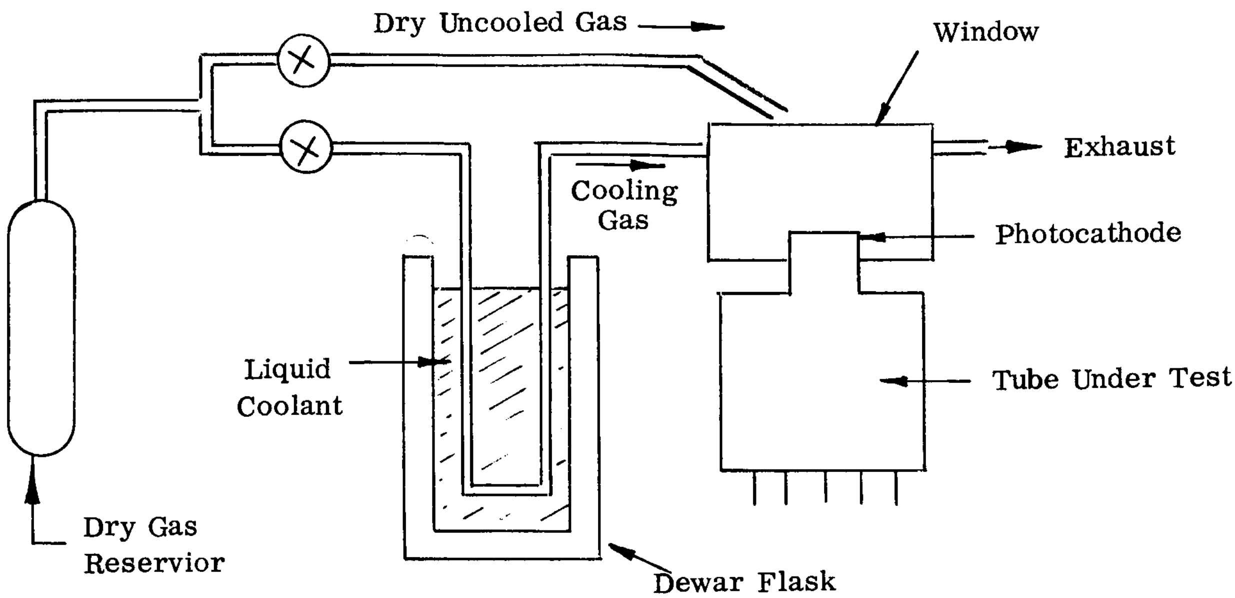

Figure 2 ITTIL Cooling Configuration

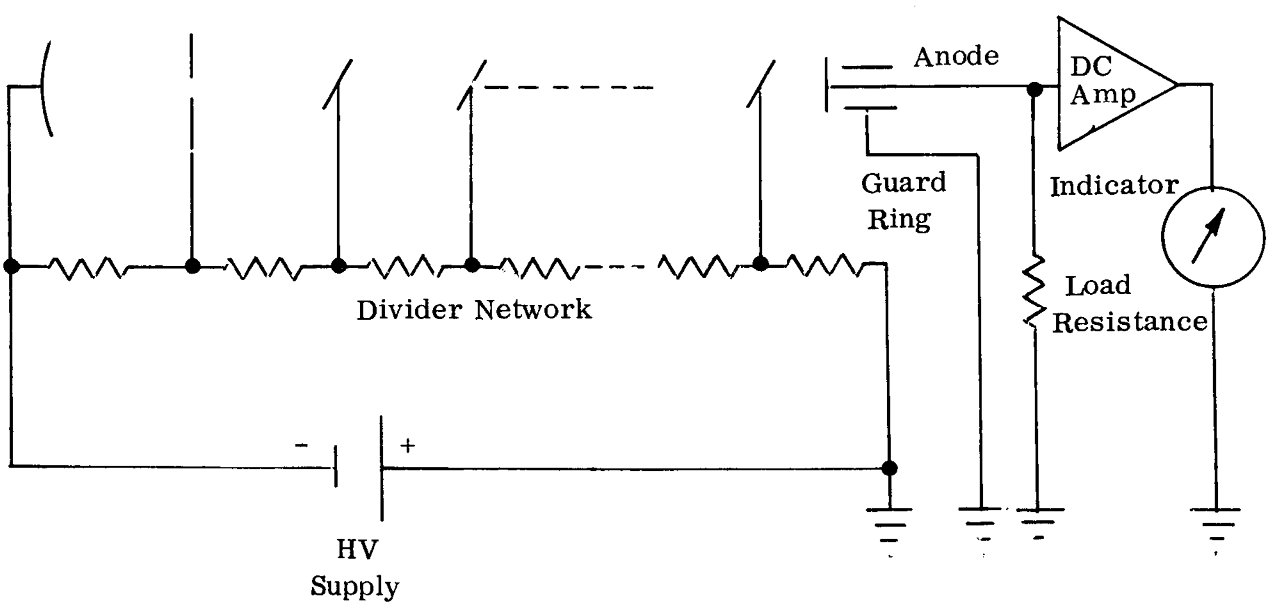

Figure 3 Typical Multiplier Phototube Circuit Using Guard Ring Electrode

applications, background light flux, present on the photocathode in the absence of the signal flux to be detected, radioactive content of the tube parts, and other dark noise sources may normally cause much more noise than photocathode thermionic emission).

The example reported by Baum in which a cooled ITTIL 16 PMI (predecessor of the present FW-118) was operated at a dark counting rate of less than 10 electrons/minute is particularly interesting. Referred to the anode circuit, under the assumption of a gain of 10^6 in the electron multiplier, this is equivalent to less than 3×10^{-14} amperes, a value well below the expected anode leakage current limits. If these 10 dark counts/minute were randomly distributed, as expected, the statistical uncertainty for a one minute observation time would have been $\sqrt{10} \cong 3$ photoelectrons, equivalent to about 13 input photons/second or a total of 750 photons in 1 minute for a peak quantum efficiency of 0.4 percent in the corresponding S-1 photocathode at 8000 Å. The ability to detect flux levels of this magnitude (approximately 3×10^{-18} watts) using single electron counting techniques with a cooled FW-118 multiplier phototube demonstrates the unique capabilities of this detector.

Cooling characteristics of S-11 and S-20 type multiplier phototubes (such as the ITTIL FW-129 and FW-130 types) are not shown in Figures 1 and 2 because of the difficulty in making reliable measurements at the dark emission rates involved. For example, a total thermionic dark count rate of only 30 electrons/second at room temperature was observed[3] in one sample ITTIL FW-129 tube. This magnitude is believed to be typical of present S-11 and S-20 tubes. Based on tentative experimental measurements it is believed that these thermionic emission dark current count rates will also fall rapidly with cooling.